A RELATIVE HUMIDITY CALIBRATION FROM 5 °C TO 45 °C IN A MIXED-FLOW HUMIDITY GENERATOR

by

Nenad D. MILOŠEVIĆ**, Nenad M. STEPANIĆ, and Marijana M. BABIĆ

Laboratory for Thermal Engineering and Energy,
Vinča Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

Original scientific paper
DOI: 10.2298/TSCI1201193M

The paper presents a method used in the Vinča Institute of Nuclear Sciences for a reliable and traceable relative humidity calibration in the temperature range from 5 °C to 45 °C. Inside a controllable temperature and humidity environment, supplied by a mixed-flow humidity generator, measurements of hygrometers under calibration are compared with those of calibrated reference instruments. A traceability chain from temperature to reference relative humidity and next to the hygrometers under calibrations is provided by using a chilled-mirror dew-point temperature system and precise relative humidity probes. Corresponding calibration uncertainties are analyzed, particularly those associated to the temperature uniformity of controlled calibration environment. Two examples of relative humidity calibration with dew-point and relative humidity reference measurements in the range from 15 to 75% of RH and 5 °C to 45 °C are presented and discussed.

Key words: *relative humidity calibration, mixed-flow humidity generator, relative humidity*

Introduction

Probably the most widely used method for expressing the water vapor content of air is percent relative humidity (RH). In many types of industries and applications, such as in the manufacture of moisture sensitive products, storage areas, energy management, computer rooms, hospitals, museums, and libraries, the influence of relative humidity is of principal importance. In practice, however, the achievable accuracy of relative humidity measurements is not as good as in many other areas of measurement and, moreover, the precise confirmation of such accuracy is not easy task to perform, even by using the most accurate calibration devices for humidity generation and measurement.

Although there are various methods for measuring relative humidity of air, all of them have advantages and disadvantages related to their accuracy and sensitivity, temperature and humidity range, stability, linearity, robustness, cost, and other parameters which may be important to specific application or user. However, for cases where a significant variation of environmental temperature takes place, the temperature dependence of applied sensor is one

* Corresponding author; e-mail: nenadm@vinca.rs

of the most important parameter which affects the accuracy of relative humidity measurements. As all relative humidity sensors are temperature sensitive and being calibrated at one temperature, they perform in a different way at other temperatures, corresponding calibration procedure should be applied for each sensor which is intended to be used in a relatively broad temperature range.

For a traceable secondary-level humidity calibration many national and accredited laboratories use two-pressure or two temperature humidity generators as a stable source of humidity and high-quality chilled-mirror dew-point (dp) temperature devices as transfer standards and/or precision thermometer in case of relative humidity calibration [1]. On the primary level, traceability is typically assured by using a primary dew-point generator [2-4], to which a sensor under calibration is directly connected. The main advantage of such application is high reliability and repeatability and lowest possible uncertainty in relative humidity calibration. On the other side, the ownership cost of such equipment could compromise this benefit for laboratories whose accreditation scope is mostly about the relative humidity calibration of industrial hygrometers. In that sense, many of these laboratories use other types of humidity generators and references such as mixed flow humidity generators or climatic chambers and psychrometers or precise capacitive relative humidity sensors [5].

The Laboratory for relative humidity from the Vinča Institute of Nuclear Sciences started its work initially with a climatic chamber and precise capacitive relative humidity sensors as basic calibration equipment [6]. During that first period, however, it became clear that the short-and long-term accuracies of used reference sensors, especially at different temperatures, have significantly affected the total calibration uncertainty. To overcome that problem, for Laboratory invested in a mixed-flow humidity generator which is capable to maintain more stable humidity and temperature conditions than that of used climatic chamber and a mid-class chilled-mirror dew-point system which is able to provide a direct traceability at different temperatures and lowest possible uncertainties of the reference relative humidity calibration. As a result, the calibration of lower-class industrial relative humidity hygrometers became more reliable and accurate over a whole temperature range.

This work describes the principle of used calibration method, relating experimental setup, and uncertainty analysis and presents the results of two typical examples of relative humidity calibration by using dew-point, *i. e.*, relative humidity reference measurements.

Principle

Relative humidity, η, is defined as the ratio in percentage between actual vapor pressure of water, e, and the saturation vapor pressure of water, e_s, at the same temperature, t. The temperature at which a condensation of vapor occurs, *i. e.*, at which air becomes saturated in equilibrium with water, is the dew-point temperature, t_d, and, therefore, the maximum relative humidity denotes the maximum vapor pressure that can exist at a given temperature.

The most accurate formula for pure saturation vapor pressure, which takes into account temperature scale ITS-90 as function of the dew-point, is given by Sonntag [7]. In presence of additional gases such as air, the saturation vapor pressure of pure water is multiplied by an enhancement factor, f, which modifies the formula for water vapor pressure to:

$$e_s(T_d, p) = f(T_d, p)e^{c_1 T_d^{-1} + c_2 + c_3 T_d + c_4 T_d^2 + c_5 \ln T_d} \tag{1}$$

where temperature $T_d = t_d + 273.15$ is given in Kelvin, while pressure e_s in Pascal. The values of constants c_1 to c_5 depend on whether the dew is water or ice, while factor f depends on gas content, absolute pressure p, and dew-point temperature. For air, atmospheric pressures, and –40 to 40 °C dew-point temperature range, the enhancement factor is about 1.004 [8].

According to its definition, relative humidity can be evaluated only by having the value of the actual vapor pressure at prevailing temperature. However, in the case of usual atmospheric conditions inside a small enclosed space, the actual vapor pressure of water can be assumed uniform and corresponding relative humidity can be computed from direct measurements of dew-point temperature and the reference temperature of surrounding air as:

$$\eta_{\mathrm{ref}}(t_{\mathrm{ref}}, t_{\mathrm{d}}) = \frac{e_{\mathrm{s}}(T_{\mathrm{d}})}{e_{\mathrm{s}}(T_{\mathrm{ref}})} \cdot 100\% \tag{2}$$

i. e., replacing the ratio (2) with the Sonntag eq. (1), as:

$$\eta_{\mathrm{ref}}(t_{\mathrm{ref}}, t_{\mathrm{d}}) = e^{c_1\left(\frac{1}{T_{\mathrm{d}}}-\frac{1}{T_{\mathrm{ref}}}\right)+c_3(T_{\mathrm{d}}-T_{\mathrm{ref}})+c_4(T_{\mathrm{d}}^2-T_{\mathrm{ref}}^2)+c_5\ln\frac{T_{\mathrm{d}}}{T_{\mathrm{ref}}}} \cdot 100\% \tag{3}$$

On the other hand, having the same conditions of the vapor pressure uniformity, a relative humidity at location x of some limited space can be computed from a single relative humidity and temperature measurement at some reference location and another temperature measurement at location x as:

$$\eta_x(t_x, t_{\mathrm{ref}}, \eta_{\mathrm{ref}}) = \eta_{\mathrm{ref}} \frac{e_{\mathrm{s}}(T_{\mathrm{ref}})}{e_{\mathrm{s}}(T_x)} \tag{4}$$

i. e., as:

$$\eta_x(t_x, t_{\mathrm{ref}}, \eta_{\mathrm{ref}}) = \eta_{\mathrm{ref}}\, e^{c_1\left(\frac{1}{T_{\mathrm{ref}}}-\frac{1}{T_x}\right)+c_3(T_{\mathrm{ref}}-T_x)+c_4(T_{\mathrm{ref}}^2-T_x^2)+c_5\ln\frac{T_{\mathrm{ref}}}{T_x}} \tag{5}$$

The principle of relative humidity calibration in this method is, therefore, straightforward: inside a small enclosed space or calibration chamber and under controlled temperature and humidity environment indications of hygrometers under calibration (HUC) are directly compared to relative humidity values obtained either from dew-point, eq. (3), or reference relative humidity measurements, eq. (5), and corresponding air temperature data.

In practice, all independent quantities in eq. (5) represent corresponding averaged values, obtained from measured data in a certain period of time, *i. e.*, during a quasi-stationary state of humidity and temperature of the calibration chamber. Considering the temperature measurements, as long as high quality calibration chambers are used, reference temperature, T_{ref}, and temperature at location x, T_x, usually have almost identical values, which implies, according to eq. (5), a proximity of relative humidity values, η_x and η_{ref}. However, due to final uncertainties of temperature measurements, uncertainty of the relative humidity at location x is much higher than that of the reference relative humidity (see the chapter *Uncertainty*).

Set-up

The main parts of the apparatus used for the relative humidity calibration are: a mixed-flow humidity generator, a chilled-mirror dew-point system, precise relative humidity probes with corresponding reading device, a set of temperature sensors with a multi-channel measurement system, a temperature calibration system, and a personal computer with in-house developed data acquisition and control software.

The model of the humidity generator is HYGROGEN 2A, manufactured by the ROTRONIC company [9]. The generator uses the mixed-flow method for generating a relative humidity environment inside its chamber: gas is humidified by a saturator and then mixed with a desiccant cell. Measurement and control is provided by a built-in relative humidity probe and a Pt100 temperature probe connected to a multi-loop controller. Temperature inside the chamber is controlled by a suitable heater and a Peltier element. Maximum achievable relative humidity and temperature ranges in the chamber are from 5% to 95% of relative humidity and from 5 °C to 50 °C. The chamber itself is in a cylindrical shape with a volume of about 2 liters and an inner air flow is controlled by a built-in fan whose rotation is not adjustable by user. The chamber is being closed from the user-side by a special door with several custom-made probe apertures.

The chilled-mirror dew-point system is a portable MBW Model 473 instrument with a separate measuring head based on the chilled mirror principle for a continuous dew-point and temperature measurements of air mixtures. The measuring head, model RP2, which is equipped with a temperature-controlled Rhodium mirror and an external precise Pt100 sensor, is placed inside the generator chamber. The head is connected to the controlling instrument, which could also serve for the acquisition and presentation of relevant data. The dew-point sensor is used for humidity measurements with a high accuracy in a dew-point temperature range from –20 °C to 70 °C. The system directly measures dew-point temperature and temperature and computes relative humidity and other humidity parameters according to eq. (2).

For relative humidity calibration of hygrometers, two capacitive relative humidity probes are used as working humidity standards in this method. The manufacturer of probes is the TESTO, model 0636 9741, and they are attached to a two-channel hand-held reading instrument of the same company, model 650. For a usual calibration, only one probe is applied for the reference relative humidity measurements, while the second is optional. Beside the relative humidity probe, a set of 15 four-wire Pt100 miniature sensors ($1.2 \times 1.6 \times 0.65$ mm) are introduced in the generator chamber for a periodical testing of chamber temperature uniformity, according to [10]. The sensors are connected outside the chamber to a 20-channel multiplexer module, model 7700, of a digital multimeter KEITHLEY, model 2700. For regular calibrations of these sensors, a system consisting of a platinum resistance thermometer, HART SCIENTIFIC, model 5618B, its reading device, FLUKE, model 1502 A, and a temperature calibration bath, HART SCIENTIFIC, model 7103, is used. The generator and all reading instruments are connected to the computer and controlled by a custom software developed in LABVIEW [11].

For assuring the traceability of relative humidity calibration, all reference sensors and instruments must be calibrated. The dew-point sensor, as a reference instrument in this set-up, is calibrated externally against the dew-point mirror of a higher class, such as the MBW 373-HX model in the MBW calibration laboratory in Switzerland, or against the primary humidity generator in the National Metrology Institute of Serbia. The traceability of the dew-point meter is then internally disseminated to the reference relative humidity probes, and then further to industrial hygrometers. Traceability of temperature measurements is assured by internal calibration of reference temperature sensors against the externally calibrated platinum resistance thermometer in the Laboratory of Metrology and Quality at the

University of Ljubljana, Slovenia. All relative humidity and temperature sensors are calibrated in loop with their indicating instruments or data acquisition systems.

Uncertainty

There are many parameters that may influence the accuracy of humidity calibration, such as the uncertainty of reference instruments, long- and short-term instabilities of reference sensors and HUC, hysteresis, linearity, reproducibility, self-heating, and resolution of applied sensors and instruments, temperature and vapor pressure distribution of applied humidity generator, pressure drop, uncertainty of eq. (1), stabilization criterion, contamination, and others. In the case of relative humidity calibration, the largest source of uncertainty is typically instability and non-uniformity of temperature inside the calibration chamber [12] and the drift and non-linearity of used relative humidity probes.

In order to get the standard uncertainties of measured relative humidity values, a derivation of eqs. (3) and (5) in respect to corresponding independent quantities is needed. If only first order derivatives are taken into account, the standard uncertainty of relative humidity for the case of dew-point reference measurements, eq. (3), can be estimated from:

$$\sigma_{\eta\mathrm{ref}}^2 \approx e^{2\left[c_1\left(\frac{1}{T_\mathrm{d}}-\frac{1}{T_\mathrm{ref}}\right)+c_3(T_\mathrm{d}-T_\mathrm{ref})+c_4(T_\mathrm{d}^2-T_\mathrm{ref}^2)+c_5\ln\frac{T_\mathrm{d}}{T_\mathrm{ref}}\right]}\cdot 10^4 \cdot$$

$$\cdot\left[\left(-\frac{c_1}{T_\mathrm{d}^2}+c_3+2c_4T_\mathrm{d}+\frac{c_5}{T_\mathrm{d}}\right)^2\sigma_{t\mathrm{d}}^2+\left(\frac{c_1}{T_\mathrm{ref}^2}-c_3-2c_4T_\mathrm{ref}-\frac{c_5}{T_\mathrm{ref}}\right)^2\sigma_{t\mathrm{ref}}^2\right] \tag{6}$$

while that for the case of relative humidity reference measurements, eq. (5), and the temperature uniformity assumption ($T_x \approx T_\mathrm{ref}$) can be found from:

$$\sigma_{\eta x}^2 \approx \sigma_{\eta\mathrm{ref}}^2 + 2\eta_\mathrm{ref}^2\left(\frac{c_1}{T_\mathrm{ref}^2}-c_3-2c_4T_\mathrm{ref}-\frac{c_5}{T_\mathrm{ref}}\right)^2\sigma_{t\mathrm{ref}}^2 \tag{7}$$

According to last relations, the standard uncertainty of computed relative humidities depends on particular standard uncertainties of measured temperatures, $\sigma_{t\mathrm{d}}^2$ and $\sigma_{t\mathrm{ref}}^2$, and on additional standard uncertainty of reference relative humidity, $\sigma_{\eta\mathrm{ref}}^2$. On the other side, all these standard uncertainties depend on other sources of uncertainty, such as those associated to reference measurements and to the performance of humidity generator, as above-mentioned.

Namely, uncertainty components from reference measurements in this method may come from short-term instabilities of readings, δt_di, δt_refi, and $\delta\eta_\mathrm{refi}$, and from imported uncertainties taken from last calibration certificates, δt_dc, δt_refc, and $\delta\eta_\mathrm{refc}$. The uncertainties associated to the resolution of reference instruments, δt_dr, δt_refr, and $\delta\eta_\mathrm{refr}$ are lower in comparison to those previously mentioned if 0.01 °Cdp, 0.01 °C, and 0.1%RH resolution is used, respectively. The uncertainties associated to the drift (long-term instability), δt_dd, δt_refd, and $\delta\eta_\mathrm{refd}$, the non-linearity, δt_dl, δt_refl, and $\delta\eta_\mathrm{refl}$, and the self-heating of reference sensors, δt_refsh, may also be significant, especially in the case of relative humidity reference measurements. Finally, uncertainties related to the contamination of reference sensors may be important, but their influence in particular has not been quantitatively estimated in this work.

The uncertainty components related to the performance of humidity generator come from a non-uniformity of temperature and relative humidity inside the calibration volume, δt_{voln} and $\delta\eta_{\mathrm{voln}}$,. As above-mentioned, these uncertainties are usually the greatest components that affect the overall calibration uncertainty in this method and the standard uncertainties of reference temperature and relative humidity measurements, σ^2_{tref} and $\sigma^2_{\eta\mathrm{ref}}$, particularly relates to this kind of uncertainty source. Moreover, for the case of the dew-point measurements, uncertainties associated to temperature non-uniformity should be considered both for the reference and the temperature measurements of the HUC because reference temperature measurements are made at the location different to that of the dew-point detection (according to a specific construction of the applied dew-point measurement head, see fig. 1. On the other side, the influence which may come from a vapor and total pressure variation inside the calibration volume has been neglected in this work due to the use of a small enclosed space with a high quality temperature and humidity control.

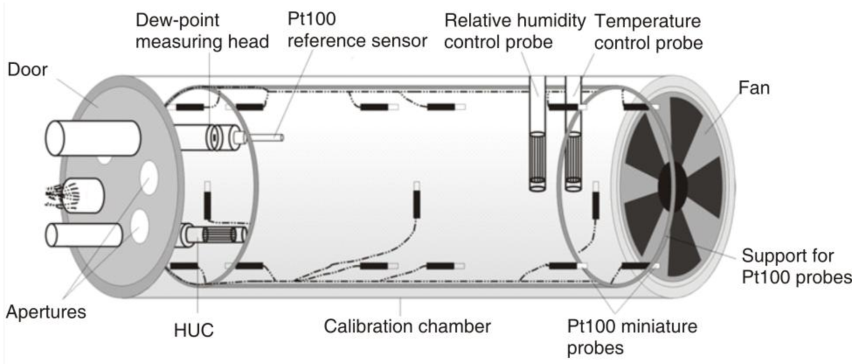

Figure 1. Calibration chamber and locations of measuring and control probes

Considering the parameters of applied HUC, instability, δt_{HUCi} and $\delta\eta_{\mathrm{HUCi}}$, resolution, δt_{HUCr} and $\delta\eta_{\mathrm{HUCr}}$, and hysteresis, $\delta\eta_{\mathrm{HUCh}}$, usually have an important influence to the overall calibration uncertainty. The same significance may have long response time, non-linearity, self-heating, contamination, and reproducibility of applied HUC, but their influences have not been quantitatively analyzed in this work.

Finally, the stabilization criterion used for both relative humidity reference measurements and measurements by HUC, $\delta\eta_{\mathrm{refs}}$, and $\delta\eta_{\mathrm{HUCs}}$, makes a contribution to the overall calibration uncertainty. This criterion defines the maximum allowable range of the relative humidity low-frequency variation during the quasi-stationary states of humidity and temperature inside the chamber.

Corresponding uncertainty budgets for two examples of relative humidity calibration by this method are presented in next chapter.

Examples

As described in the chapter *Set-up*, the traceability of relative humidity calibration is provided by using the dew-point system and platinum resistance thermometer as primary standards and precise relative humidity and temperature probes as working standards. In order to demonstrate this method, two calibration examples are described: In the first, the dew-point system has been used for the calibration of one precise relative humidity probe in the temperature and relative humidity range from 5 °C to 45 °C and 15 °C to 75% of relative humidity, while in the second example, the same reference relative humidity probe has been applied for the calibration of another relative humidity probe in the same temperature and relative humidity range. Related uncertainty budgets for both examples are computed and presented according to recommendations given in [13].

Calibration using the dew-point system

In this example, calibration of one relative humidity probe connected with its reading device (TESTO probe 0636 9741; device 650) has been performed by using described chilled-mirror hygrometer. The head of the dew-point meter was put inside the chamber of the humidity generator through sealed door apertures. Temperature was measured by the Pt100 external sensor installed at the top of the head and fifteen Pt100 miniature sensors connected to scanner at different locations inside the chamber, as described in the chapter *Set-up*. Locations of all measuring probes inside the chamber are shown in fig. 1.

An illustration of measured values during the calibration at reference temperatures of 5, 15, and 25 °C is given in fig. 2. The lower graph at the l. h. s. shows the variation of dew-point temperature, t_d, and the reference temperature, t_{ref}. The upper one shows a variation of the reference relative humidity, η_{ref}, calculated from the two temperatures according to eq. (2), and that of the relative humidity of the HUC, η_{HUC}, on a same time scale. It can be

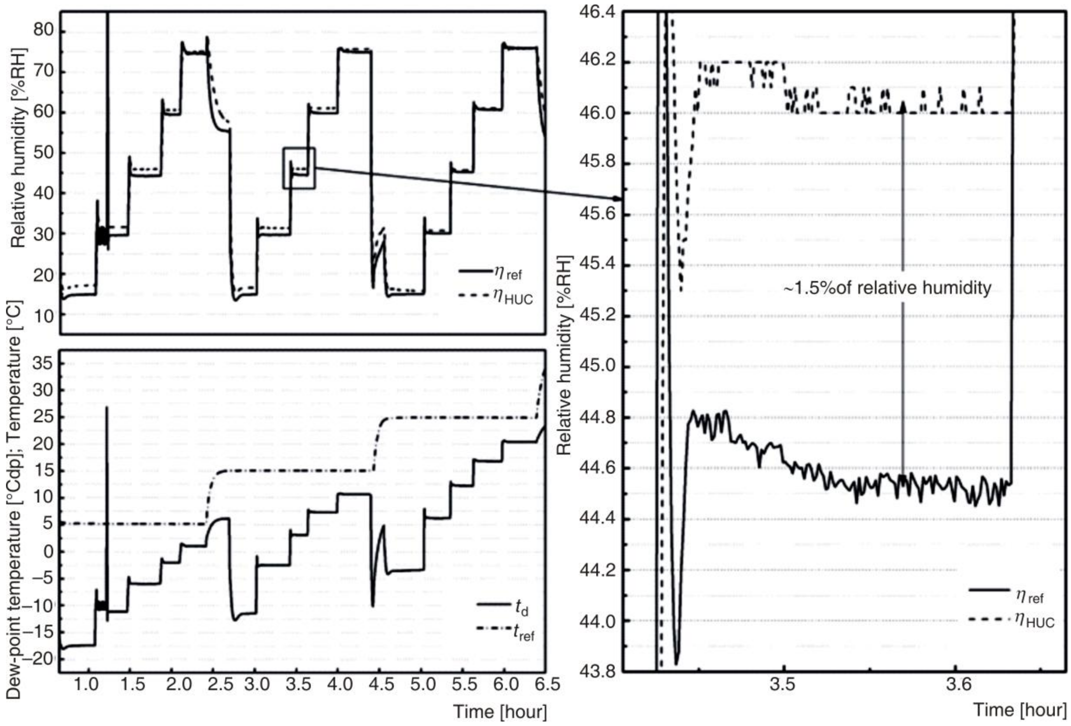

Figure 2. Example of measuring data in function of time

seen that each stationary reference relative humidity relates to corresponding dew-point temperature and to reference temperature plateau. For data evaluating process, however, a simultaneous stabilization of the readings of HUC is also needed. In enlarged graph on the r. h. s. of fig. 2, a comparative variation of two relative humidities during a stationary dew-point temperature is presented. According to that, the reading of the HUC deviates from the reference relative humidity for about 1.5% of relative humidity at the reference temperature of 15 °C.

Having the most important influence on calibration uncertainty, results of the chamber temperature uniformity have been particularly analyzed according to [10] and at each reference temperature from 5 °C do 45 °C. Having results presented in fig. 3, the best chamber uniformity is achieved around room reference temperatures, while it gets worse as temperature goes toward the cooling and heating limits. For example, at reference temperature of 15 °C, the parameter of temperature non-uniformity, δt_{voln}, which includes the uncertainty of temperature measurements as well, is equal to about 0.16 °C.

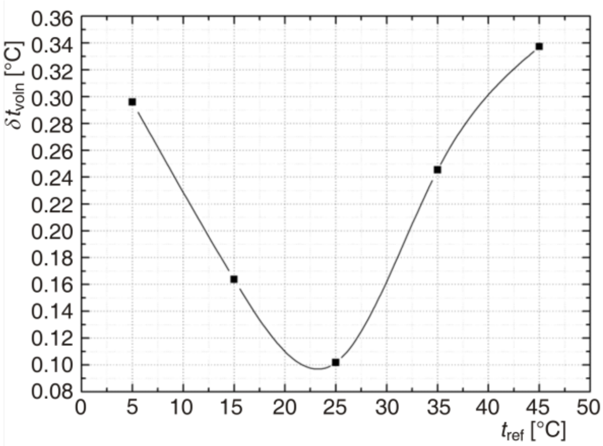

Figure 3. Temperature non-uniformity of calibration chamber at different stationary temperatures

An example of uncertainty budget for the values from the r. h. s. of fig. 2 is presented in tab. 1. A reference relative humidity of 44.55% RH has been obtained from eq. (3) for an average dew-point and reference temperature of 3.07 °C and 15.04 °C, t_{dav} and t_{refav}, respectively. Sensitivity coefficients have been computed by using eq. (6) and corresponding dew-point and reference temperature values and the influence of each uncertainty component has been evaluated in percentage relative humidity. An average indication of the HUC of 46.0% RH, and 14.9 °C, η_{HUCav} and t_{HUCav}, has been found, with the overall expanded calibration uncertainties, $U_{\eta\mathrm{HUC}}$ and $U_{t\mathrm{HUC}}$, of 0.7% RH and 0.2 °C, respectively, computed both from the uncertainties of reference relative humidity and temperature and also from those specific to the applied HUC.

Analyzing the values of dew-point and reference temperatures, corresponding relative humidities and readings of HUC at all stationary reference temperatures from 5 °C to 45 °C, the final calibration results for the relative humidity of HUC are presented in fig. 4. The differences or deviations between HUC readings and reference relative humidities, $\eta_{\mathrm{HUC}} - \eta_{\mathrm{ref}}$, in function of η_{HUC} for all stationary temperatures, t_{ref}, are shown in the l. s. h. graph, while the values of expanded calibration uncertainties for relative humidity, $U_{\eta\mathrm{HUC}}$, are presented on the other graph of fig. 4. These results clearly reveal a strong temperature dependence on HUC relative humidity readings.

Considering the temperature, the deviations between HUC and relating reference temperatures have been from –0.4 °C to 0.5 °C, with the overall uncertainty range from 0.2 °C to 0.5 °C.

Table 1. Example of the uncertainty budget of the relative humidity calibration at 45% and 15 °C by using the dew-point temperature system

Quantity	Description	Value	Unc.	Prob.	Divisor	Unit	Stand. dev.	Sens. coeff.	Unit	Stand. unc.	Expand. unc.
t_{refav}	Average value of reference temperature	15.04	0.002	Normal	2	°C	0.001	2.868	%RH	0.003	–
δt_{refc}	Correction due to the last calibration of reference temperature	0	0.030	Normal	2	°C	0.015	2.868	%RH	0.043	–
δt_{refd}	Correction due to the drift of reference temperature	0	0.010	Rectang.	1.732	°C	0.006	2.868	%RH	0.017	–
δt_{refl}	Correction due to the non-linearity of reference temperature	0	0.007	Rectang.	1.732	°C	0.004	2.868	%RH	0.011	–
δt_{refi}	Correction due to the instability of reference temperature reading	0	0.008	Normal	2	°C	0.004	2.868	%RH	0.011	–
δt_{refr}	Correction due to the resolution of reference temperature reading	0	0.006	Rectang.	1.732	°C	0.003	2.868	%RH	0.010	–
δt_{refsh}	Correction due to the self-heating of reference temperature	0	0.010	Rectang.	1.732	°C	0.006	2.868	%RH	0.017	–
δt_{voln}	Correction due to the temperature non-uniformity of calibration chamber	0	0.162	Normal	2	°C	0.081	2.868	%RH	0.232	–
$\boldsymbol{t_{ref}}$	**Reference temperature**	**15.04**	–	–	–	°C	0.083		%RH	0.238	–
t_{dav}	Average value of dew-point temperature	3.07	0.002	Normal	2	°Cdp	0.001	3.157	%RH	0.003	–
δt_{dc}	Correction due to the last calibration of dew-point system	0	0.050	Normal	2	°Cdp	0.025	3.157	%RH	0.079	–
δt_{dd}	Correction due to the drift of dew-point system	0	0.100	Rectang.	1.732	°Cdp	0.058	3.157	%RH	0.182	–
δt_{dl}	Correction due to the non-linearity of dew-point system	0	0.020	Rectang.	1.732	°Cdp	0.012	3.157	%RH	0.036	–
δt_{di}	Correction due to the instability of dew-point temperature reading	0	0.020	Normal	2	°Cdp	0.010	3.157	%RH	0.032	–
δt_{dR}	Correction due to the resolution of dew-point temperature reading	0	0.006	Rectang.	1.732	°Cdp	0.003	3.157	%RH	0.011	–
$\boldsymbol{t_{d}}$	**Dew-point temperature**	3.07	–	–	–	°Cdp	0.065	–	%RH	0.205	–
$\boldsymbol{\eta_{ref}}$	**Reference relative humidity**	**44.55**	–	–	–	–	–	–	%RH	0.314	–
η_{HUCav}	Average value of the relative humidity of HUC	46.0	0.01	Normal	2	%RH	0.00	1	%RH	0.00	–
$\delta\eta_{HUCi}$	Correction due to the instability of relative humidity reading of HUC	0	0.08	Normal	2	%RH	0.04	1	%RH	0.04	–
$\delta\eta_{HUCr}$	Correction due to the resolution of relative humidity reading of HUC	0	0.06	Rectang.	1.732	%RH	0.03	1	%RH	0.03	–
$\delta\eta_{HUCh}$	Correction due to the hysteresis of relative humidity reading of HUC	0	0.20	Normal	2	%RH	0.10	1	%RH	0.10	–
η_{HUCs}	Correction due to the stabilization criterion of relative humidity of HUC	0	0.20	Rectang.	1.732	%RH	0.12	1	%RH	0.12	–
$\delta\eta_{voln}$	Correction due to the relative humidity non-uniformity of calibration chamber	0	0.20	Rectang.	1.732	%RH	0.12	1	%RH	0.12	–
$\boldsymbol{\eta_{HUC}}$	**Relative humidity of HUC**	**46.0**	–	–	–	–	–	–	%RH	0.37	**0.7**
t_{HUCav}	Average value of the temperature of HUC	14.9	0.00	Normal	2	°C	0.00	1	°C	0.00	–
δt_{HUCi}	Correction due to the instability of temperature reading of HUC	0	0.00	Normal	2	°C	0.00	1	°C	0.00	–
δt_{HUCr}	Correction due to the resolution of temperature reading of HUC	0	0.06	Rectang.	1.732	°C	0.03	1	°C	0.03	–
δt_{voln}	Correction due to the temperature non-uniformity of calibration chamber	0	0.16	Normal	2	°C	0.08	1	°C	0.08	–
$\boldsymbol{t_{HUC}}$	**Temperature of HUC**	**14.9**	–	–	–	–	–	–	°C	0.12	**0.2**

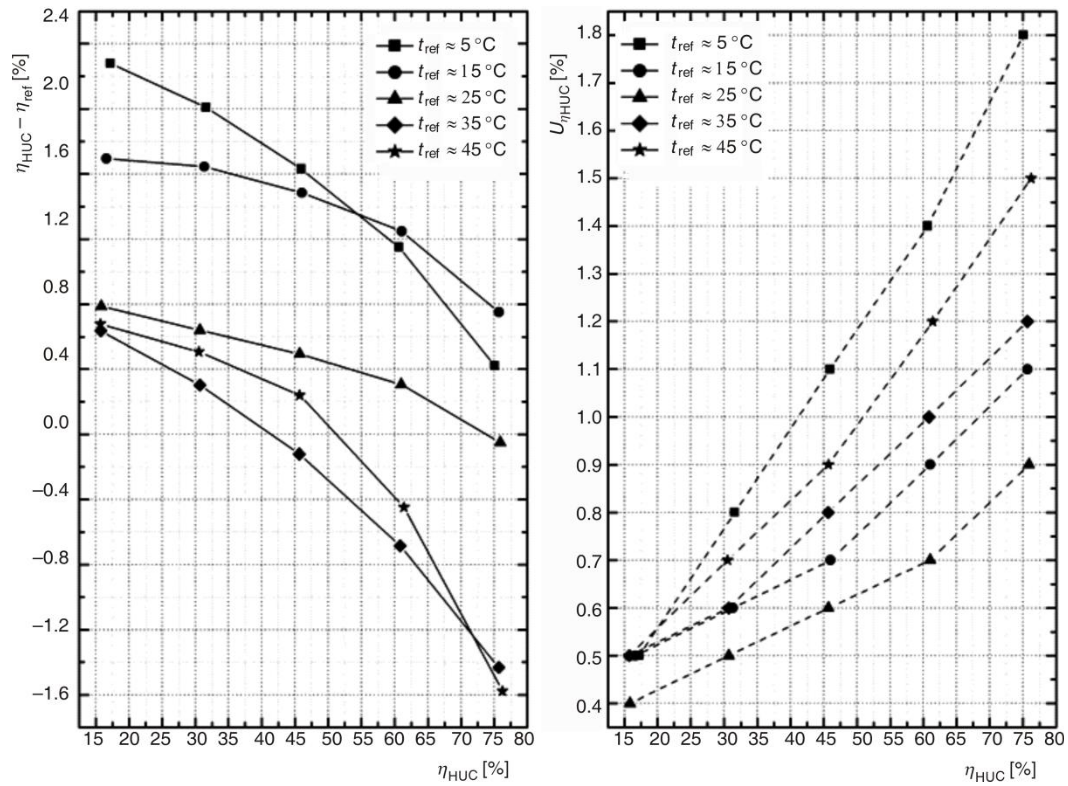

Figure 4. Calibration results obtained by using the dew-point system as a reference

Calibration using the reference relative humidity probe

By using the relative humidity probe previously calibrated by the dew-point system, an example of traceable calibration of another relative humidity probe of the same type is presented in this section. Having the same calibration set-up as shown in fig. 1, but with the second relative humidity probe instead of the dew-point head, the same measurement procedure has been carried out.

An example of uncertainty budget for values obtained at approximately same temperature and relative humidity conditions as given in previous example is presented in tab. 2. It can be seen that although the uncertainty associated to temperature non-uniformity is not applied in reference relative humidity measurements as it was done in the first example (tab. 1), an expanded uncertainty of relative humidity calibration is almost twice higher. The main reasons are much higher imported uncertainty from last calibration, as well as the drift and non-linearity of the applied for reference relative humidity probe.

On the same manner as in the first example, final results of relative humidity calibration in this case are presented in fig. 5. According to them, deviations from reference relative humidity depends both on stationary temperature and relative humidity values, as expected. However, in this example, these differences may be indiscernible in practice due to a high level of corresponding calibration uncertainties.

Table 2. Example of the uncertainty budget of the relative humidity calibration at 45% and 15 °C by using a reference relative humidity probe

Quantity	Description	Value	Unc.	Prob.	Divisor	Unit	Stand. dev.	Sens. coeff.	Unit	Stand. unc.	Expand. unc.
t_{refav}	Average value of reference temperature	15.0	0.00	Normal	2	°C	0.00	4.017	%RH	0.00	–
δt_{refc}	Correction due to the last calibration of reference temperature	0	0.20	Normal	2	°C	0.10	4.017	%RH	0.40	–
δt_{refd}	Correction due to the drift of reference temperature	0	0.10	Rectang.	1.732	°C	0.06	4.017	%RH	0.23	–
δt_{refi}	Correction due to the instability of reference temperature reading	0	0.02	Normal	2	°C	0.01	4.017	%RH	0.04	–
δt_{refr}	Correction due to the resolution of reference temperature reading	0	0.06	Rectang.	1.732	°C	0.03	4.017	%RH	0.13	–
δt_{refsh}	Correction due to the self-heating of reference temperature	–0.03	0.02	Rectang.	1.732	°C	0.01	4.017	%RH	0.03	–
$\boldsymbol{t_{ref}}$	**Reference temperature**	**15.0**	**–**	**–**	**–**	°C	0.12	–	%RH	0.49	**–**
η_{refav}	Average value of reference relative humidity	45.6	0.01	Normal	2	%RH	0.00	1	%RH	0.00	–
$\delta\eta_{refc}$	Correction due to the last calibration of of reference relative humidity	–1.5	0.74	Normal	2	%RH	0.37	1	%RH	0.37	–
$\delta\eta_{refd}$	Correction due to the drift of reference relative humidity	0	0.50	Rectang.	1.732	%RH	0.29	1	%RH	0.29	–
$\delta\eta_{refl}$	Correction due to the non-linearity of reference relative humidity	0	0.40	Rectang.	1.732	%RH	0.23	1	%RH	0.23	–
$\delta\eta_{refi}$	Correction due to the instability of reference relative humidity reading	0	0.03	Normal	2	%RH	0.02	1	%RH	0.02	–
$\delta\eta_{refr}$	Correction due to the resolution of reference relative Humidity reading	0	0.06	Rectang.	1.732	%RH	0.03	1	%RH	0.03	–
$\delta\eta_{refs}$	Correction due to the stabilization crite-rion of reference relative humidity	0	0.20	Rectang.	1.732	%RH	0.12	1	%RH	0.12	–
η_{ref}	**Reference relative humidity**	**44.1**	–	–	–	–	–	–	%RH	0.54	–
η_{HUCav}	Average value of the relative humidity of HUC	45.0	0.01	Normal	2	%RH	0.00	1	%RH	0.00	–
$\delta\eta_{HUCi}$	Correction due to the instability of relative humidity reading of HUC	0	0.04	Normal	2	%RH	0.02	1	%RH	0.02	–
$\delta\eta_{HUCr}$	Correction due to the resolution of relative humidity reading of HUC	0	0.06	Rectang.	1.732	%RH	0.03	1	%RH	0.03	–
$\delta\eta_{HUCh}$	Correction due to the hysteresis of relative humidity reading of HUC	0	0.20	Normal	2	%RH	0.10	1	%RH	0.10	–
η_{HUCs}	Correction due to the stabilization criterion of relative humidity of HUC	0	0.20	Rectang.	1.732	%RH	0.12	1	%RH	0.12	–
$\delta\eta_{voln}$	Correction due to the relative humidity non-uniformity of calibration chamber	0	0.20	Rectang.	1.732	%RH	0.12	1	%RH	0.12	–
$\boldsymbol{\eta_{HUC}}$	**Relative humidity of HUC**	**45.0**	–	–	–	–	–	–	%RH	0.75	**1.5**
t_{HUCav}	Average value of the temperature of HUC	15.0	0.00	Normal	2	°C	0.00	1	°C	0.00	–
δt_{HUCi}	Correction due to the instability of temperature reading of HUC	0	0.02	Normal	2	°C	0.01	1	°C	0.01	–
δt_{HUCr}	Correction due to the resolution of temperature reading of HUC	0	0.06	Rectang.	1.732	°C	0.03	1	°C	0.03	–
δt_{voln}	Correction due to the temperature non-uniformity of calibration chamber	0	0.16	Normal	2	°C	0.08	1	°C	0.08	–
$\boldsymbol{t_{HUC}}$	**Temperature of HUC**	**15.0**	–	–	–	–	–	–	°C	0.15	**0.3**

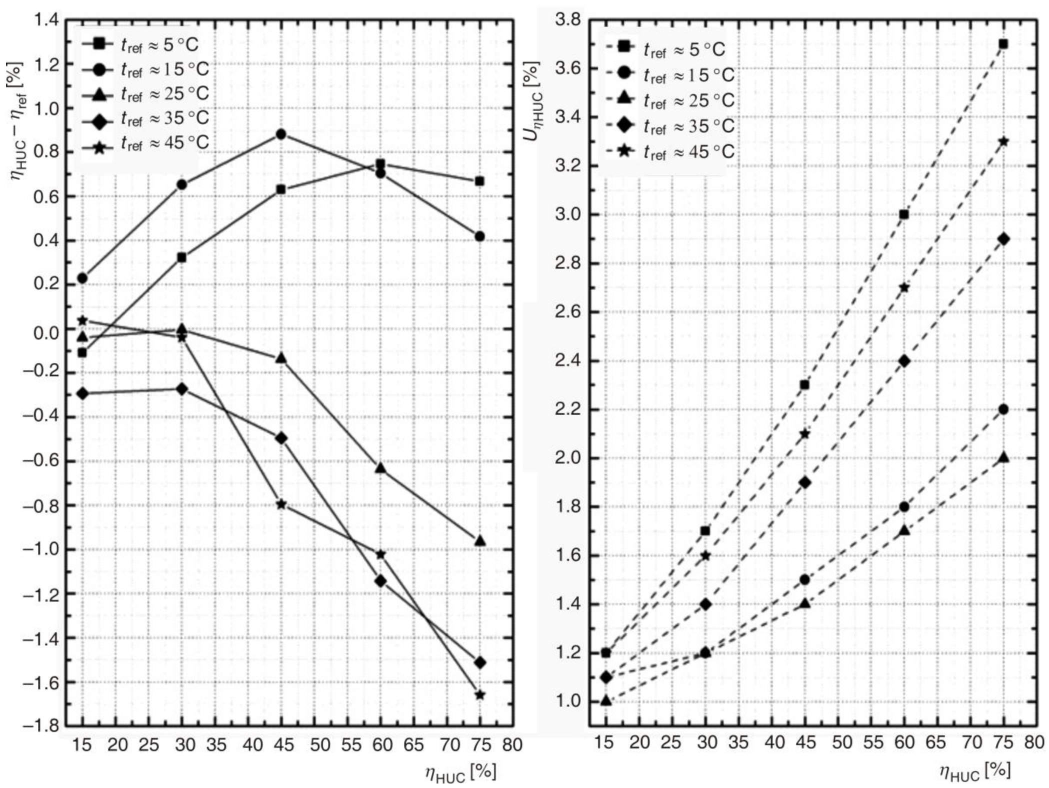

Figure 5. Calibration results obtained by using the relative humidity probe as a reference

Conclusions

Generation of desired humidity environment at temperatures other than ambient is important for the calibration of relative humidity sensors which usually exhibit significant temperature dependence. Due to its relatively high temperature stability and uniformity at different stationary temperatures, a mixed-flow humidity generator is applied as the main tool for relative humidity calibration in this work. On the other side, traceability and reference relative humidity measurements are directly provided from a reliable chilled-mirror dew-point system, which is used as transfer standard from dew-point temperature to relative humidity, and next, from precise relative humidity sensors to hygrometers under calibration.

Presented calibration method and setup used in the Vinča Institute, together with in-house developed control and data acquisition software, assure calibration results and uncertainties with an unbroken traceability chain from high level humidity standards to industrial hygrometers. With such measurement procedure and equipment, the temperature dependence hygrometers under calibration can be straightforwardly observed and quantified.

References

[1] Wiederhold, P. R., Water Vapor Measurement, Methods and Instrumentation, Marcel Dekker Inc., New York, USA, 1997

[2] Hudoklin, D., Drnovšek, J., The New LMK Primary Standard for Dew-Point Sensor Calibration: Evaluation of the High-Range Saturator Efficiency, *International Journal of Thermophysics, 29* (2008), 5, pp. 1652-1659
[3] Hudoklin, D., *et al*., Design and Validation of a New Primary Standard for Calibration of the Top-End Humidity Sensors, *Measurement*, *41* (2008), 9, pp. 950-959
[4] Heinonen, M., *et al*., Investigation of the Equivalence of National Dew-Point Temperature Realizations in the −50 °C to + 20 °C Range, *International Journal of Thermophysics*, (in press) DOI: 10.1007/s10765-011-0950-x
[5] ***, A Guide to the Measurement of Humidity, The Institute of Measurement and Control, London, 1996
[6] Milošević, N. D., Stepanić, N. M., Laboratory for the Relative Humidity in the Vinča Institute (in Serbian), NIV-ITE 387/ML, Belgrade, 2008
[7] Sonntag, D., Important New Values of the Physical Constants of 1986, Vapour Pressure Formulations Based on the ITS-90, and Psychrometer Formulae, *Zeitschrift fur Meteorologie*, *40* (1990), 5, pp. 340-344
[8] Greenspan, L., Humidity Fixed Points of Binary Saturated Aqueous Solutions, *Journal of Research of the National Bureau of Standards*, *81A* (1977), 1, pp. 89-96
[9] Ramsey, B., Farley, R., The Development of a Transportable Humidity and Temperature Generator, Asian Environmental Technology, Hertfordshire, UK, 2006 (http://www.envirotech-online.com/articles/evironmental-analysis/7/blue_ramsey_robin_farley/the_development_of_a_transportable_humidity_and_temperature_generator/201
[10] ***, A Guide to Calculating the Uncertainty of the Performance of Environmental Chambers, The Society of Environmental Engineers, Buntingford, UK, 2003
[11] Babić, M. M., Stepanić, N. M., Milošević, N. D., Virtual Instrument for Adjustment, Control, Display, and Data Acquisition in a Relative Humidity and Dew-Point Temperature Calibration Procedure by Using Different High-Performance Multifunctional and Multichannel Devices (in Serbian), NIV-ITE 477/ML, Belgrade, 2011
[12] Heinonen, M., Uncertainty in Humidity Measurements, EUROMET Workshop P758, MIKES Publication J4/2006, Esppo, Finland, 2006
[13] ***, EA-4/02:1999, Expression of the Uncertainty of Measurement in Calibration, European Co-operation for Accreditation, Paris, 1999

Paper submitted: June 1, 2011
Paper revised: December 21, 2011
Paper accepted: December 30, 2011